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Preliminary Investigation on Determining the Minimum Cement Content in Rigid Pavements

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PRELIMINARY INVESTIGATION ON DETERMINING THE MINIMUM CEMENT CONTENT IN RIGID PAVEMENTS

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ABSTRACT

This paper presents the preliminary results of an experimental program that consists of testing of concrete mixtures with varying water-to-binder ratios (w/b) and cementitious contents. The purpose of this laboratory study is to investigate the minimum cement content that can be used in rigid pavements without sacrificing the performance (i.e., strength and durability). Initially, 16 mixes using only portland cement and 48 mixes incorporating supplementary cementitious materials, namely class F fly ash, class C fly ash and slag as portland cement replacement at levels of 20%, 20% and 40%, respectively, were planned. This paper reports the results of a subset of this study. Concrete mixtures with w/b ranging from 0.43 to 0.65 and cementitious content ranging from 400 lb/yd^3 to 700 lb/yd^3 were designed. Compressive strength, chloride penetration and air permeability were determined. The findings of the study with the available data are as follows: strength is a function of w/b and independent of the binder content; air permeability increases as w/b and binder content increase; among all the mixtures containing different type and amount of cementitious materials, slag cement provides the lowest 28 day chloride penetration whereas class C fly ash results in the highest chloride penetration.

(198 words/250 max)

INTRODUCTION

Concrete durability is commonly specified by defining minimum cement content, minimum strength, and maximum free water-to-cement ratio (w/c) *(1)*. The w/c is the main factor affecting concrete strength where lower w/c provides higher strength. However, it is also perceived that concrete strength is controlled by the cement content *(2-3)*. Based on this perception, minimum cement content is often specified conservatively and may exceed the amount needed for the desired strength and durability. A drawback of such practice is the increased cost as portland cement is the most expensive component of concrete. Moreover, it is estimated that the cement industry emits approximately 5% of global carbon dioxide (CO_2); hence, more portland cement means more CO_2 emission.

High cement content generally contributes to a much greater strength than the required design strength and even more cement is required to achieve the desired low w/c *(4)*. High cement content may cause workability and finishability problems in fresh concrete, hence, affecting the durability of hardened concrete. Concrete shrinkage is a function of w/c and cement content. With an increasing cement content, the shrinkage is found to be increased *(5)*.

The addition of cementitious materials may also lead to poor performance such as plastic shrinkage associated with cracking due to their hydration, setting and bleeding characteristics *(4-9)*. There is therefore, a need to investigate how to use cement more efficiently. This project aims to find the minimum cementitious content for a concrete mixture that is optimized for workability, durability and strength in rigid pavements. Since the proposed study will investigate efficient usage of cement content in concrete production, it is likely that costs will also be reduced.

METHODOLOGY

Materials

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A single batch of each of the following commercially available materials was obtained:

- ASTM C150 Type I ordinary portland cement
- ASTM C618 Class F fly ash
- ASTM C618 Class C fly ash
- ASTM C989 Slag cement
- 1 inch nominal maximum size crushed limestone
- No 4 nominal maximum size river sand
- ASTM C494 Type F polycarboxylate based high range water reducer (HRWR)

Test Variables

The full test program includes 64 different mixture combinations with w/b ranging from 0.43 to 0.65. The cementitious content is also used as a test variable and the levels utilized are 400, 500, 600 and 700 lb/yd^3 (pcy). 33 mixtures out of 64 mixture combinations have been prepared and tested at the time this paper was written.

Four different cement systems were tested-100% Type I portland cement, also referred as the control, 80% Type I portland cement with 20% Class F fly ash, 80% Type I portland cement with 20% Class C fly ash, and 60% Type I portland cement with 40% slag. Fine and coarse aggregates were combined at a ratio of 1:1.38 and kept constant for all the concrete mixtures so that the void content of the combined gradation would remain the same for all the mixtures. If necessary, slump measured by ASTM C143, was adjusted to a minimum of 2 inches using a high range water reducer. No air entraining admixture was used.

Test Procedures

4×8-in concrete cylinders were cast in accordance with ASTM C31. Compressive strength was determined at 1, 3, and 28 days using the cylinders according to ASTM C39. 2- and 1-inch thick disks were cut from the cylinders for chloride penetration resistance (ASTM C1202), and for air permeability, based on the University of Cape Town Method *(10)*, respectively. Chloride penetration was determined at the age of 28 days and air permeability was determined at the age of 1, 3, and 28 days.

Air permeability index *(10)* is the negative log of the Darcy coefficient of permeability (m/s) and uses a log scale. Thus, higher air permeability index indicates the more impermeability of the concrete *(11)*. The air permeability coefficients are affected by the changes in curing duration, test age and concrete composition *(12)*.

RESULTS

Compressive Strength

Compressive strength test was performed on 33 out of 64 mixtures at 1, 3 and 28 days. Table 1 summarizes the results of the plain portland cement mixes.

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TABLE 1 Compressive Strength Test Results at 1, 3 and 28 Days of Plain Concrete Mixtures

Mix Proportions			Compressive Strength, psi		
No	**w/b**	**Cement (pcy)**	**1 day**	**3 day**	**28 day**
1	0.43	700	3377	4857	7420
2	0.44	600	3161	4795	7173
3	0.47	500	2683	4656	7348
4	0.47	700	2418	4143	6665
5	0.49	600	2333	4099	6544
6	0.51	400	2467	4360	7487
7	0.52	500	1920	3800	6328
8	0.52	700	2121	3446	5760
9	0.55	400	1940	3614	6182
10	0.57	700	1777	2968	4904
11	0.59	600	1923	3063	5697
12	0.60	400	1442	2621	4984
13	0.61	500	1212	2200	4500
14	0.65	400	Not available		4256

The effect of cement content at the various w/b on compressive strength is presented in Figures 1 - 3. The trends shown in Figures 1-3 are consistent with the information in the literature *(2, 3 and 9)* that strength is independent of cement content for a given w/b: compressive strength decreases as w/b increases.

The highest 1 day compressive strength, 3377 psi, was achieved by the mixture with the w/b of 0.43 and700 pcy of cement content, whereas the lowest 1 day compressive strength, 1212 psi, was obtained by the mixture with the w/b of 0.61 and 500 pcy of cement content. The same trend is observed for the 3 day results.

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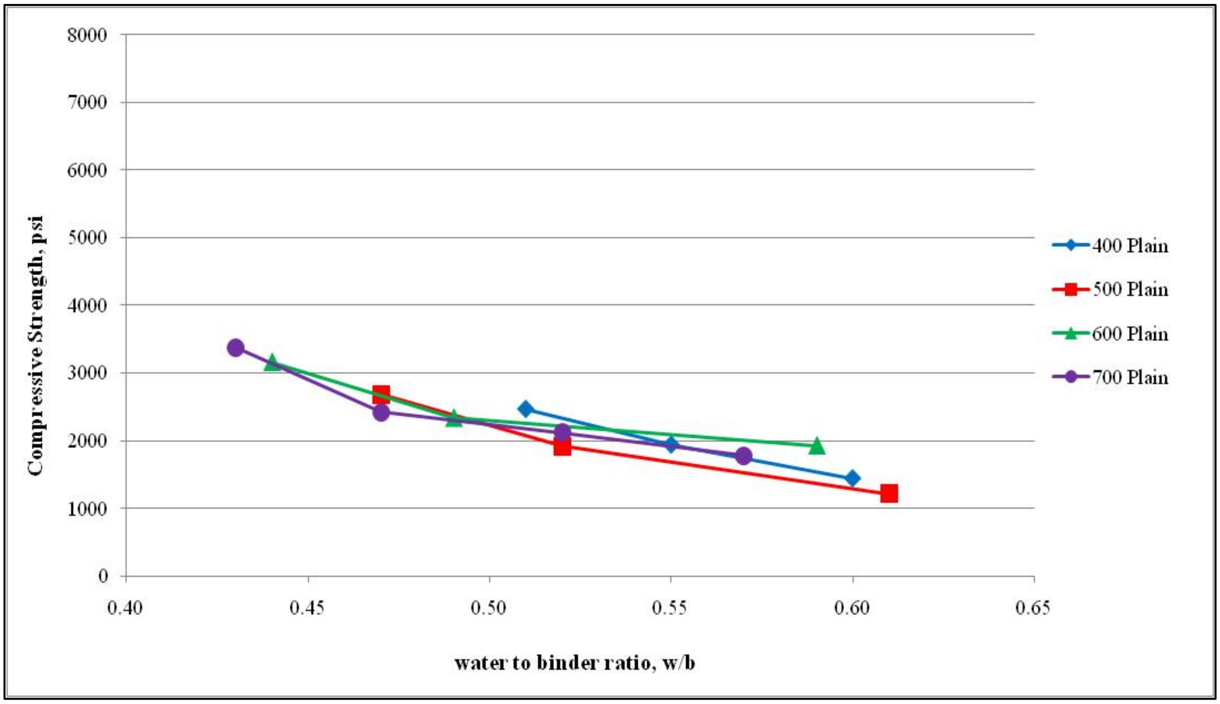

FIGURE 1 Effect of various cement content with different w/b on 1 day compressive strength.

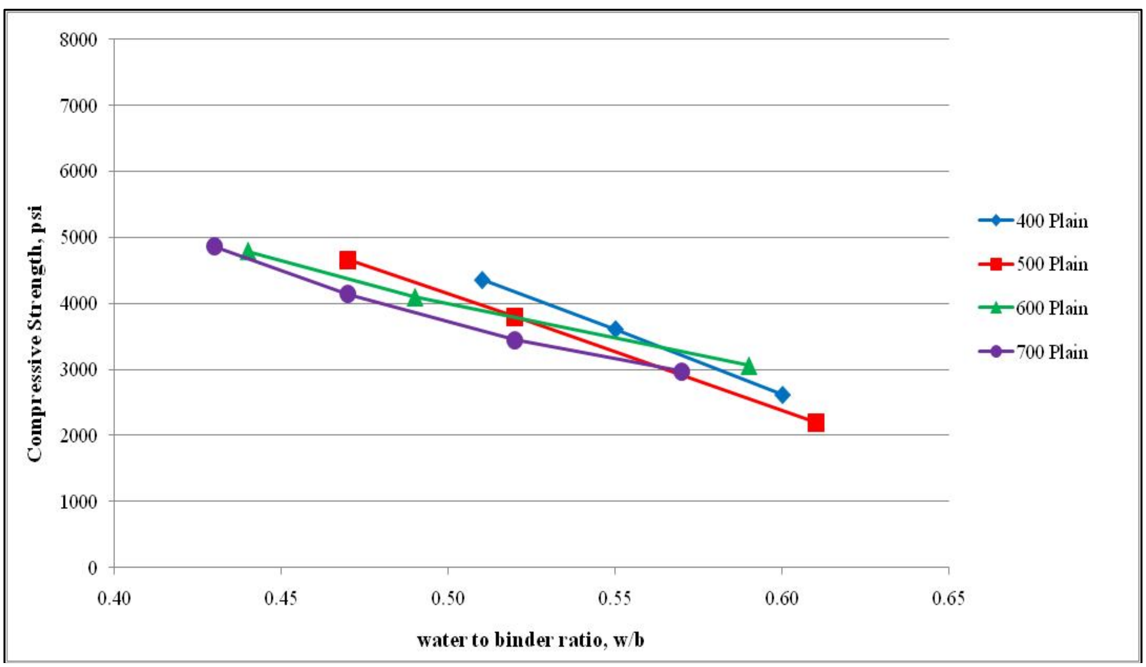

FIGURE 2 Effect of various cement content with different w/b on 3 day compressive strength.

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The highest 28 day compressive strength, 7487 psi, was achieved by the mixture with the w/b of 0.51 and 400 pcy of cement content, whereas the lowest 28 day compressive strength, 4256 psi, was obtained by the mixture with the w/b of 0.65 and 400 pcy of cement content.

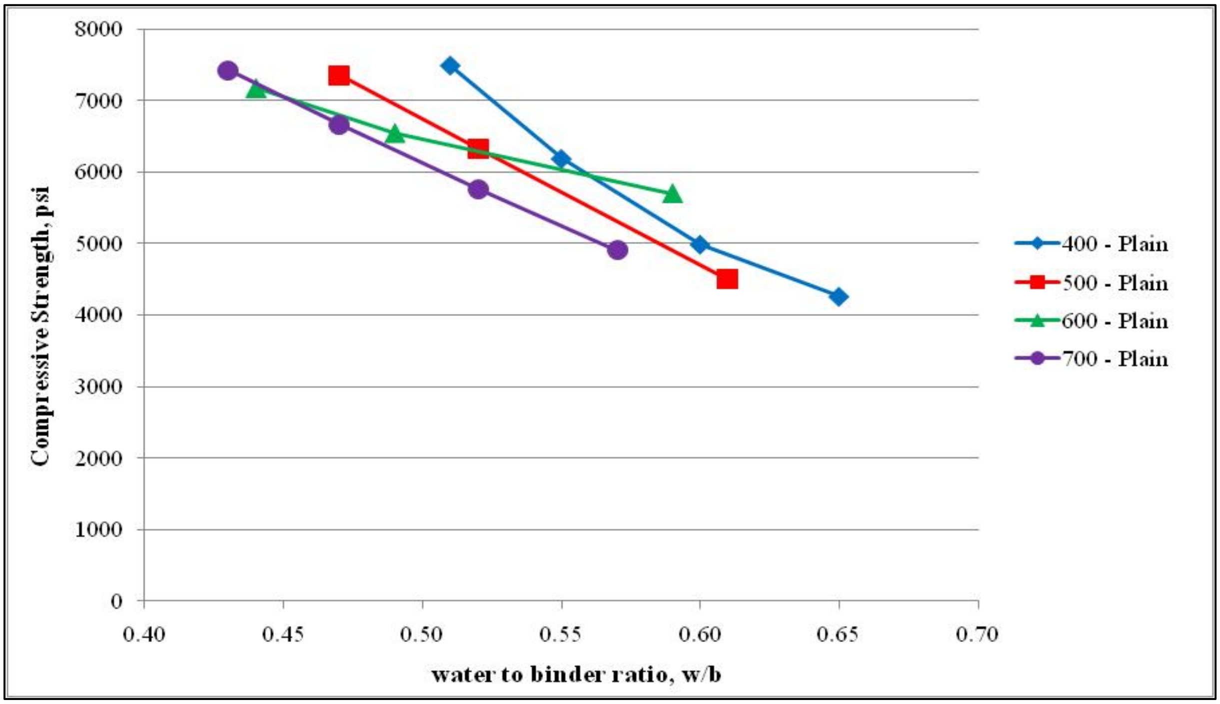

FIGURE 3 Effect of various cement content with different w/b on 28 day compressive strength.

As shown in Figures 1-3, the mixtures depict a trend that strength decreases with increase in w/b. However, the ratio of this decrement varies depending on the cement content. .
The compressive strength test results of 33 mixtures containing different type and amount of cementitious materials at different w/b are presented in Figures 4-6.

The 1-day compressive strength results show that the highest strength among all the mixtures was achieved by the plain concrete mixture containing only portland cement as cementitious material whereas the lowest strength was obtained by the mixture containing slag. The mixtures showed an overall decrease in 1-day strength trend with the increasing w/b. Data thus far is limited but based on the decrement rate among the mixtures it can be stated that strength decreases as the w/b increases.

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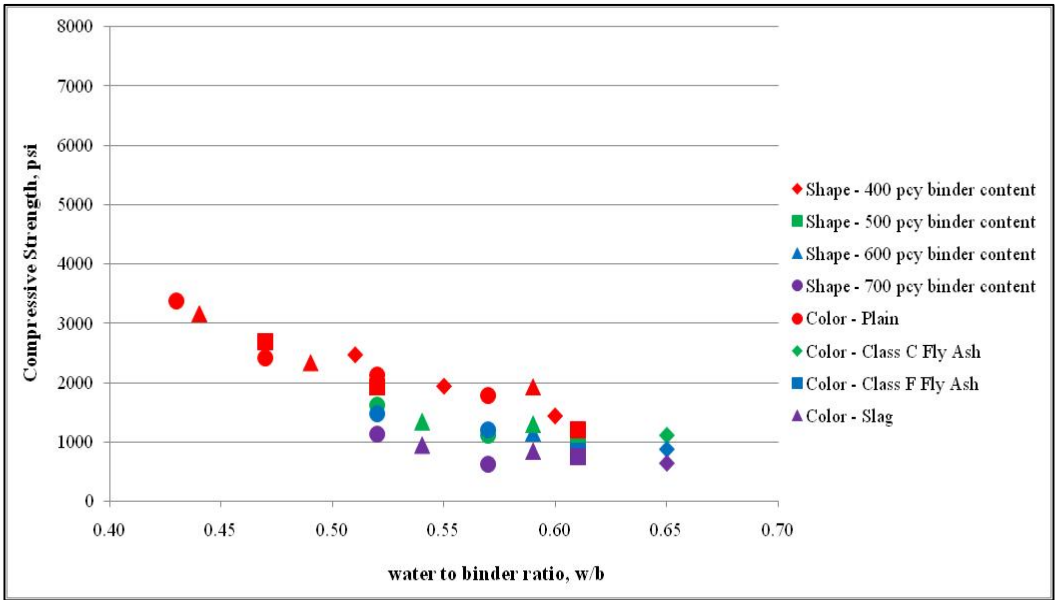

FIGURE 4 Effect of cementitious materials content with different w/b on 1 day compressive strength.

The 3- day compressive strength results show the same characteristics with the 1-day strength results.

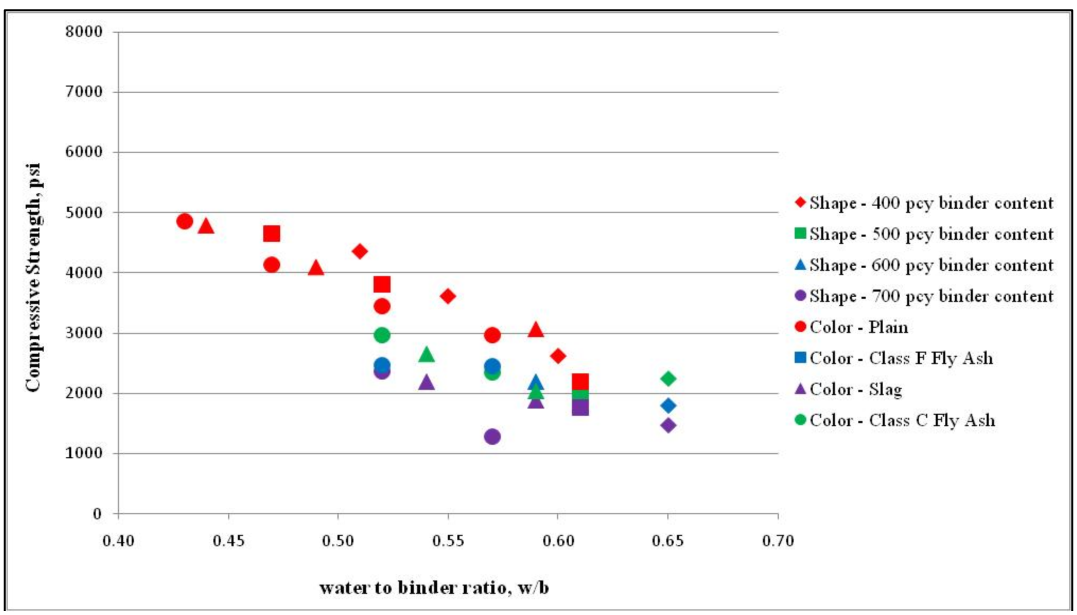

FIGURE 5 Effect of cementitious materials content with different w/b on 3 day compressive strength.

The 28- day compressive strength results show a different behavior than 1 and 3-day strength results. The highest strength among all the mixtures was again achieved by the plain concrete mixture containing only portland cement as cementitious material whereas the lowest

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strength was obtained by the mixture containing Class F fly ash. This result indicates that the aging factor plays an important role on the concretes containing different type of supplementary cementitious materials. The mixtures showed an overall decreasing 28-day strength trend with the increasing w/b. Data thus far is limited but based on the decrement rate among the mixtures it can be stated that 28-day compressive strength significantly decreases as the w/b increases. The plot in Figure 6 shows that strength does not decrease systematically as the binder content changes. The variety of mixtures with lower binder content supplying higher strength than the mixtures with higher binder content (especially when w/b is lower than 0.50) shows that strength is not dependent on the binder content.

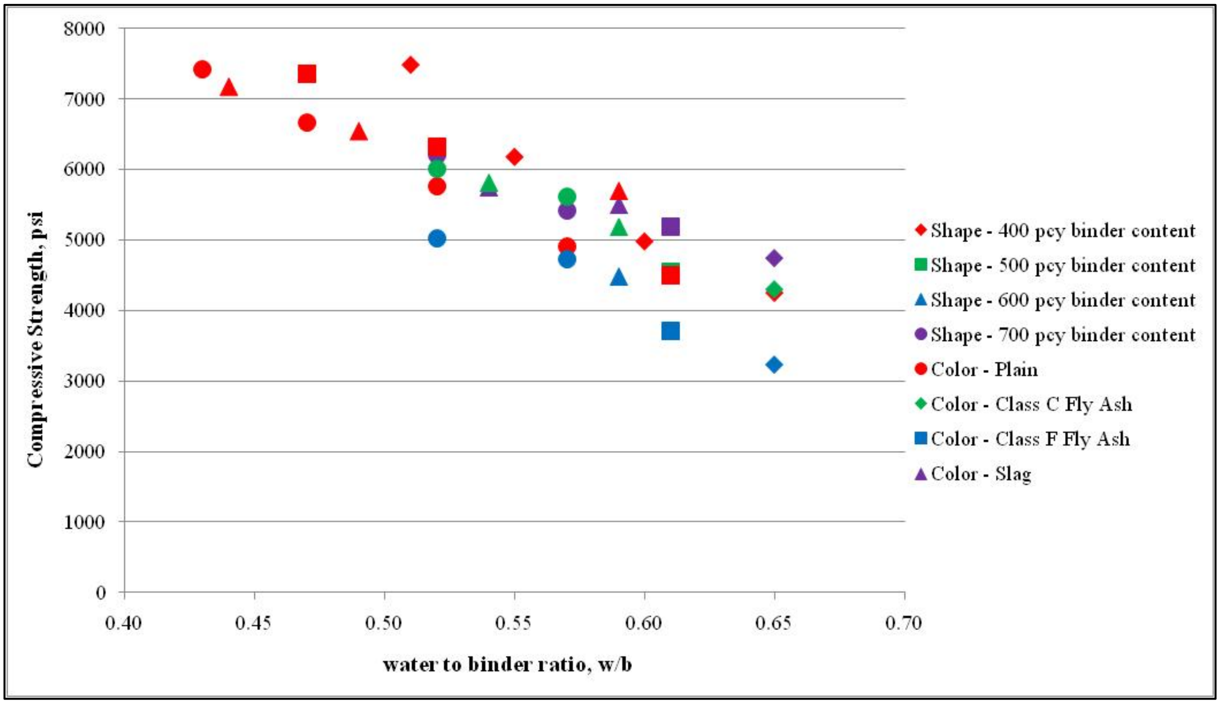

FIGURE 6 Effect of cementitious materials content with different w/b on 28 day compressive strength.

Effect of w/b for a Given Cement Content on Compressive Strength

This part focuses on the results that were obtained from the fourteen plain portland cement concrete mixtures with different w/b. The effect of w/b for a given cement content on 1, 3 and 28 day compressive strength is presented in Figures 7 - 9. The trends shown in Figures 7 - 9 are consistent with the information in the literature *(2, 3, 5 and 9)* that strength is a function of the w/b in the concrete.

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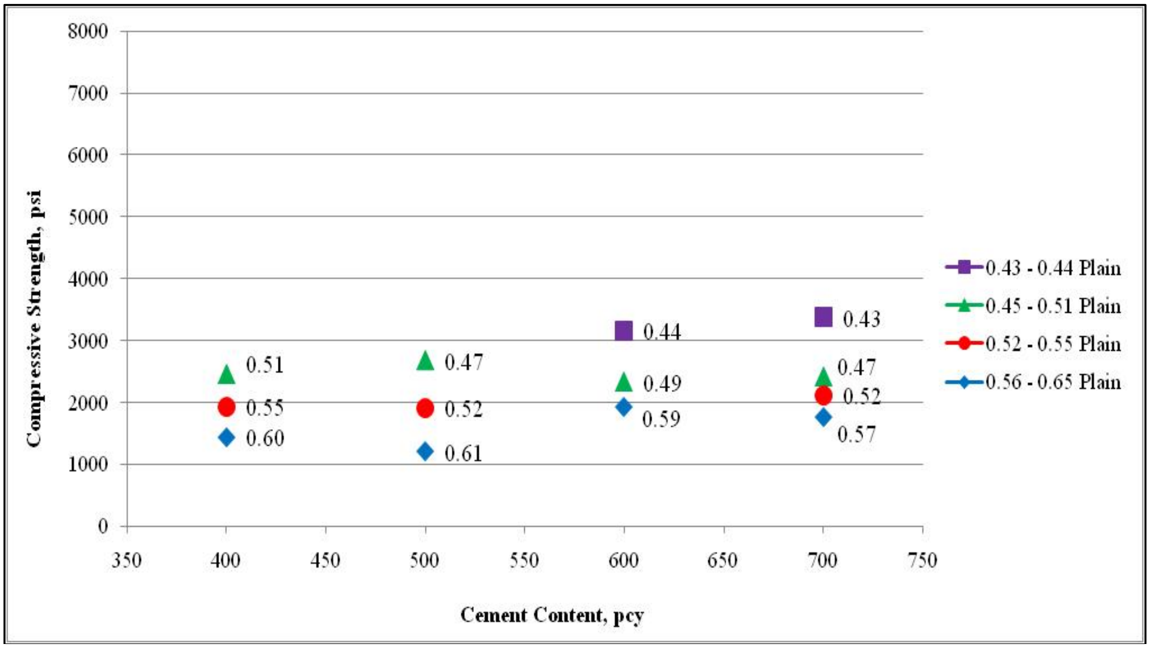

FIGURE 7 Effect of different w/b with various levels of cement content on 1 day compressive strength.

It can be seen in Figures 7 and 8 that the overall highest 1 and 3 day compressive strength was achieved by the mixture with the lowest w/b, 0.43, whereas the overall lowest 1 and 3 day compressive strength was obtained by the mixture with the highest w/b, 0.61.

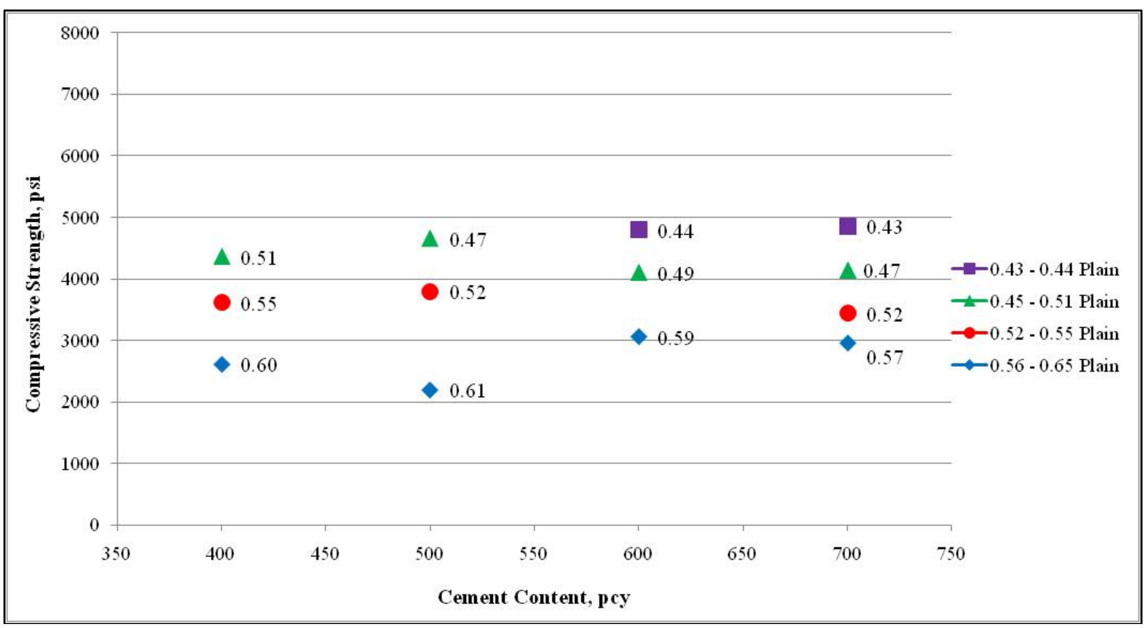

FIGURE 8 Effect of different w/b with various levels of cement content on 3 day compressive strength.

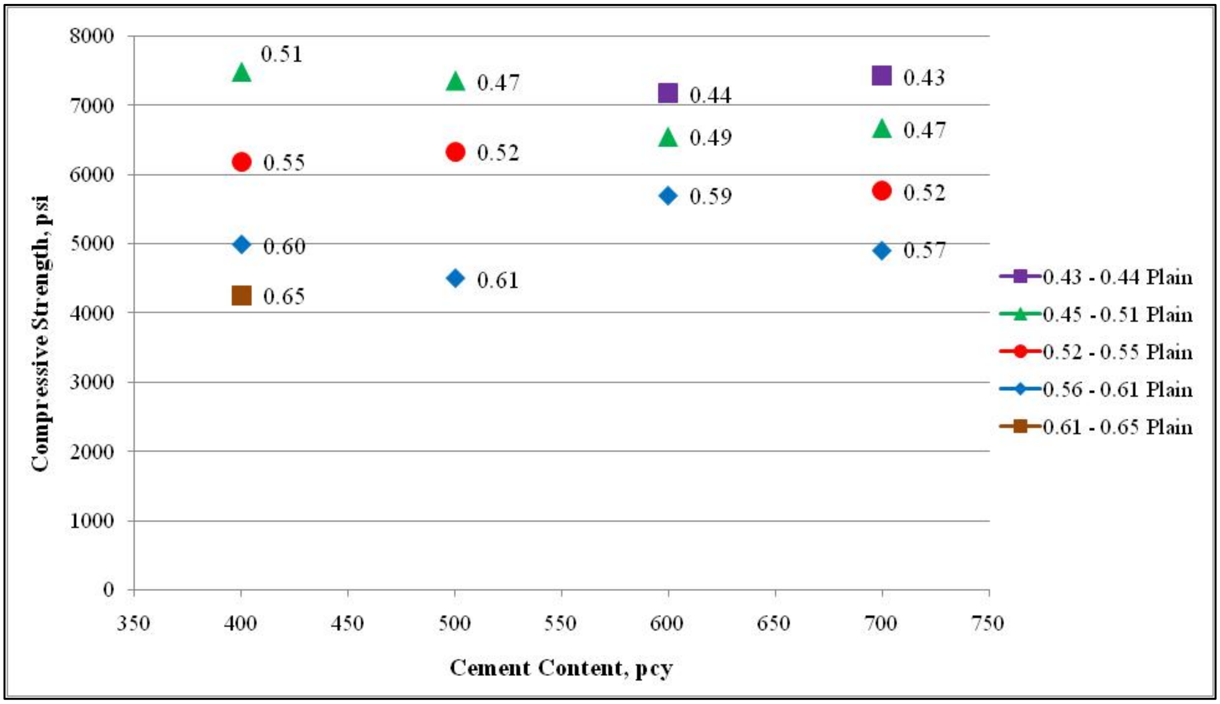

FIGURE 9 Effect of different w/b with various levels of cement content on 28 day compressive strength.

Data thus far is limited; however, the color coding that represents the range of w/b in Figures 7 -9 shows that for a given range of w/b, the strength results are independent of cement content.

Air Permeability

This section presents the air permeability results that were obtained from concrete mixtures produced with varying binder contents and w/b. Air permeability test was performed at 1, 3 and 28 days. The results are presented in Figure 10.

Results of the 3-day air permeability test are plotted in Figure 10. For a given cement content of 500 or 700 pcy, the mixtures with higher w/b provide higher air permeability than the mixtures with lower w/b. This shows that for a given cement content, the higher the w/b, the more permeable is the concrete. Similarly, for a given w/b, increasing cement content tends to make the mixture more permeable. These results are in good agreement with the literature *(10-12)*.

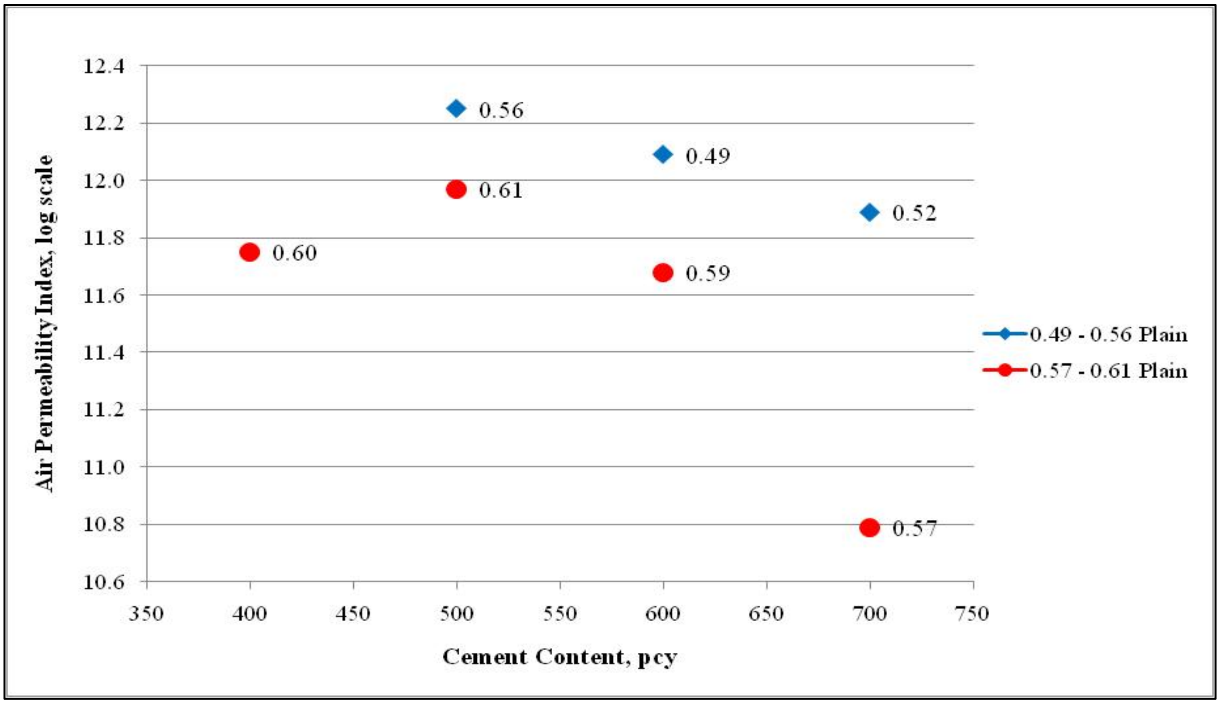

FIGURE 10 Effect of plain concrete at different w/b with various levels of cement content on 3 day air permeability.

Chloride Penetration Resistance

The chloride penetration test results of 19 concrete mixes with different amount and type of cementitious materials at various levels of w/b are presented in Figure 11. The tests were performed at 28 days of age.

Figure 11 shows an increasing chloride penetration rate (as given in coulombs) up to w/b of 0.57 then a decreasing trend with increase in w/b. Figure 11 also suggests that most of the mixtures provided higher chloride penetration resistance with the decreasing binder content. When the binder content was kept constant, the mixes with lower w/b provided higher permeability compared to the high w/b mixes. However, data is limited and no significant relationship can be established at this point.

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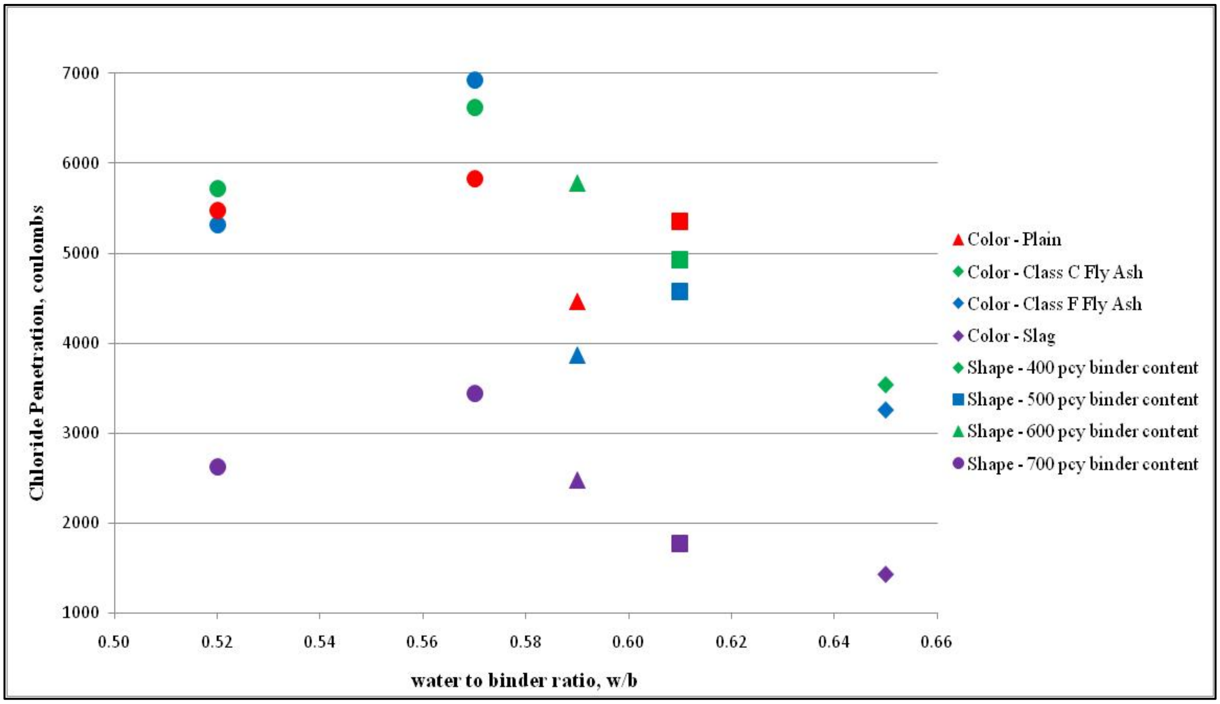

FIGURE 11 Relationship between chloride penetration at 28 day and w/b for different types and amount of cementitious materials.

DISCUSSION

Effect of Cement Content on Compressive Strength

The compressive strength results of plain concretes showed that strength decreases as the w/b increases and is not affected much by the cement content (Figures 1- 3). It might be stated that strength is independent of cement content for a given w/b. The results suggest that 'more cement in a mix means a better performing mix' might be a misconception.

The results demonstrate that strength is dependent on the w/b: as it is seen in Table 1, the lowest w/b resulted in the highest 1 day compressive strength whereas the lowest 1 day compressive strength was obtained by the mix with the highest w/b. Figure 3 shows that the lowest 28 day compressive strength was obtained with the mix with 400 pcy of cement, however, the highest compressive strength value was also obtained by the mixture with 400 pcy of cement content. This shows that the highest and lowest compressive strength values are not dependent on the cement content but w/b: for a given cement content, the highest strength was achieved by the mix with the lowest w/b and the lowest strength was obtained by the highest w/b. For 400 pcy mix with w/b of 0.65, the compressive strength tests at the age of 1 and 3 days failed due to severe honeycombing. The paste content of this mixture was quite low and at the early age the mixes did not develop sufficient bonding. It was very difficult to obtain a uniform mixture at the mixing stage. The placeability and finishability of the mixture were also very problematic. The slump of this mixture was determined as 0.2 inches. As a result, most of the samples experienced honeycombing problems as shown in Figure 12.

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FIGURE 12 Honeycombing occurred in the mixture containing 400 pcy cement content at a w/b of 0.65.

Air Permeability

In Figure 10, the overall trend shows that air permeability decreases as w/b decreases. As expected high w/b leads to a more porous paste thus increasing air penetration. Furthermore, air permeability increases as binder content increases. This is attributed to the increased capillary porosity as a result of the increased paste content. Cement paste is considered to have a more porous structure as compared dense natural aggregate, therefore, air penetrates faster through the paste.

Chloride Penetration Resistance

The obtained results show that among all the mixtures containing different type and amount of cementitious materials, slag cement provides the lowest coulombs passed. The lowest chloride resistance, or the highest coulombs passed, was observed in the mixes containing class C fly ash for most of the mixes with varying w/b and binder content. Furthermore, it was found that the less the binder content is, the less coulombs passed by the mixtures containing supplementary cementitious materials. Given the limited data, a significant relationship between w/b and chloride penetration cannot be established at this stage of the study.

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CONCLUSIONS

Based on the available data following conclusions can be drawn:

1. Strength is a function of w/b.
2. Strength is independent of binder content for a given w/b.
3. Air permeability increases as w/b increases with increasing binder content. The influence of the amount of coarse aggregate in concrete mix on the air permeability should be further studied.
4. Among all the mixtures containing different type and amount of cementitious materials, slag cement provides the lowest chloride penetration.

These results suggest that the strength and durability of concrete could be improved by optimizing the mixture proportions. However, it is recommended that further investigation is needed to quantify the effects of optimization on the long term strength and durability.

ACKNOWLEDGMENT

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